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Technical Report

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HEAT-TRANSFER STUDIES OF DROPWISE CONDENSATION AND THIN-FILM EVAPORATION

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

HEAT-TRANSFER STUDIES OF DROPWISE CONDENSATION AND THIN-FILM EVAPORATION

Y-R011-01-009

Type C Final Report

by

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ABSTRACT

Experiments were conducted to investigate heat-transfer rates from water-film evaporation and dropwise condensation. Dropwise condensation was induced by coating the external surface of the heat-exchanger tubes with a polytetrafluoroethylene polymer, and film evaporation was obtained by allowing water to fall in a thin film around the surface of the tube. The effect of tube length and feed flow on the overall heat-transfer coefficient was also investigated. The overall heat-transfer coefficients obtained from the dropwise condensation experiments were considerably greater than those obtained from the film-type condensation experiments conducted to obtain comparison data. Overall heat-transfer coefficients as high as 4000 Btu/sq ft/F/hr were obtained from the dropwise condensation experiments as compared to values of about 700 Btu/sq ft/F/hr that were obtained from the film-type condensation. The results of thin-film evaporation on the internal surface of the tube were inconclusive.

INTRODUCTION

The total quantity of heat transferred in evaporators may be affected by changes in temperature drop or by changes in the overall coefficient. The overall coefficient is affected by changes in the steam-film coefficient and the liquid-film coefficient. Although the mechanism of heat transfer in the liquid film is very complex and very little data is available, three principal factors that affect it are known:[1] (1) the velocity of the liquid past the heating surface, (2) the viscosity of the liquid, and (3) the geometrical arrangement and condition of the heating surface.

The mechanism of heat transfer in the steam film is better known than that for the liquid film. When the steam condenses on a metal surface, the condensation may take place in either of two forms. One of the forms is known as film-type condensation, which occurs when the steam wets the surface on which it is condensing. The other is known as dropwise condensation, which occurs when the steam does not wet the surface on which it is condensing but collects in the form of drops that fall off the surface, leaving an apparently unwetted surface where new drops can form. The steam-film coefficients obtained from dropwise condensation are larger than those obtained from film-type condensation.

Both forms of condensation may take place at the same time, but, in general, smooth clean surfaces tend to induce film-type condensation, and oily or greasy surfaces tend to induce dropwise condensation. The use of oily or greasy materials is not very practical because they are washed away and have to be replaced continuously, and, in most cases, they impart undesirable odor and taste to the distilled water.[2]

Since the overall heat-transfer coefficient is affected by changes in the steam- and water-film coefficients, the experimental work was directed toward the investigation of overall heat coefficients, combining the effects of dropwise condensation and water-film evaporation.

For this task, a polytetrafluoroethylene polymer[2] was selected to induce dropwise condensation because it does not wet nor wash away. Water-film evaporation was obtained from a thin film of water falling on the surface of a vertical tube.

DESCRIPTION OF EQUIPMENT

The experimental work was made in two vertical evaporators: a single-tube unit and a multiple-tube unit. Two test series were made on single-tube units and one series on the multiple-tube unit.

The single-tube evaporator had a 1-inch-OD, 16-BWG, cupro-nickel tube mounted inside a shell of 3-inch glass pipe sections. The length of the tube was made a variable parameter for these runs. Figures 1 and 2 show the single-tube evaporator at its maximum length. For one series of runs, the top section of the evaporator was adapted with an orifice plate to produce a thin film of water falling on the external surface of the tube (Figure 3 is the flow diagram). For the other series of runs, the top section of the evaporator was adapted with an orifice provided with a plug that projected into the tube, leaving an annular space from which water ran down on the internal surface of the tube in the form of a thin film (Figure 4 is the flow diagram). There were no means to ascertain that the water inside the tube was actually flowing in the form of a thin film, but, for practical purposes, it was assumed.

The steam for this single-tube apparatus was supplied by an oil-fired steam generator. The pressure of the steam from the generator was reduced to about 3.0 psig by a pressure-reducing valve in the inlet side of the evaporator. The feedwater was preheated with steam in a shell-and-tube heat exchanger. The feed flow was controlled by a float-valve in a variable-hydraulic-head storage tank.

In setting up the single-tube apparatus, some difficulty was encountered in controlling the thickness of the film falling on the external surface of the tube. The apparatus used for this is shown in Figure 5. An orifice was used at the top of the tube, and the hydraulic head on the orifice was varied to change the thickness of the water film. A 1-1/16-inch orifice plate produced the most uniform coverage and film thickness for the purpose of the investigation. For the falling film on the internal surface of the tube, an orifice plate was adapted, with a plug that projected about 0.75 inch down the opening of the tube to form an annular space about 1/16 inch wide within the tube.

The multiple-tube evaporator, a shell-and-tube unit, consisted of thirty-seven 1-inch-OD, 10-foot-long, 16-BWG, cupro-nickel tubes and a steel shell. The exteriors of the tubes were coated thinly with a polytetrafluoroethylene polymer; the thickness of the coat averaged about 0.001 inch. The evaporator was operated as a thermocompression unit by using the components (except for the evaporator body) of an 85-gph distillation unit. Figure 6 shows the 37-tube evaporator, the diesel engine, and the compressor.

EXPERIMENTAL RUNS WITH THE SINGLE-TUBE EVAPORATOR

The first series of runs was made on a single, bare tube. The falling film was on the external surface of the tube, and the heating steam was inside the tube.

The second series of runs was made on a single, coated-exterior tube. The falling film was on the internal surface of the tube and the heating steam condensed on the external, coated surface of the tube. A run was also made on this evaporator with the tube stripped of the coating.

During these two series, the length of the tube was varied, by cutting sections of different lengths, to determine the effect of tube length on the overall heat-transfer coefficient.

Distilled water was used for all tests. The temperature of the water flows were read from thermometers inserted in the flow lines entering and leaving the evaporator. The temperatures of the steam and evaporating water were obtained from steam tables[3] by using the pressure readings in the steam side and in the evaporating water side of the evaporator.

Constant operating conditions were maintained for the duration of each run, except that during the first series of runs, the temperature of the feed could not be kept constant. The variation in temperature was due to fluctuations in the steam flow entering the feed heater. In the subsequent series of runs no attempt was made to obtain a definite feed temperature below 212 F. Figure 7 shows the results of the first series with the bare tube and a falling film on the outside of the tube. The overall heat-transfer coefficient is plotted against the feed flow rates and tube lengths.

The second series of runs was conducted under similar operating conditions but with the film evaporation on the internal surface of the tube and steam condensation on the external surface of the tube. Figure 8 shows the overall heat-transfer coefficient plotted against the feed flow rates and tube lengths for dropwise condensation on the coated surface, and Figure 9 shows the coefficients for film condensation on the uncoated surface of the tube.

EXPERIMENTAL RUNS WITH THE 37-TUBE EVAPORATOR

A series of runs was made in the 37-tube evaporator, with all the tubes coated externally with the polytetrafluoroethylene polymer. For these experiments, the length of the tubes was constant, the falling film was on the internal surface of the tube, and the heating steam was on the external surface of the tube.

For these runs, the tubes were partially filled with water, and attempts were made to run the tests with falling film alone, but feedwater could not be distributed uniformly to all the tubes. Figure 10 shows the overall heat-transfer coefficient plotted against water level and compressor speed.

RESULTS

The overall heat coefficients obtained from the 37-tube-unit runs were in the same order of magnitude as those obtained from the single bare-tube unit. However, it was apparent that in the 37-tube unit, only a fraction of the heat transfer was taking place from the condensing steam to the falling film since not all the tubes were wetted by the falling water. The overall heat-transfer coefficients obtained from the single, coated tube with dropwise condensation were considerably greater than those obtained from the other runs.

The overall heat-transfer coefficients for the single, bare tube ranged from 450 to 700 Btu/sq ft/F/hr, with feed flows of 5 to 30 gph and tube lengths from 4.5 to 8.0 feet. For the single, coated tube, the coefficients ranged from 1000 to 4000 Btu/sq ft/F/hr with feed flows of 8.0 to 26.0 gph and tube lengths from 2.5 to 8.5 feet. The highest coefficient was obtained from the shortest tube length and the highest feed flow rate.

The overall heat coefficient for the 37-tube unit ranged from 400 to 650 Btu/sq ft/F/hr. The length of the tube was 10 feet. The level of the water in the tubes varied from 0.3 to 7.0 feet. Three runs were made with three compressor speeds: 925, 800, and 700 rpm. Although the level of the water affected the overall coefficient, the effect did not seem to be very significant.

The summarized data of the heat-transfer coefficients from the three series of runs is presented in Table I.

COMPARISON DATA

The typical range of data on heat-transfer coefficients for a short-tube, calandria-type evaporator operating at about atmospheric pressure and overall temperature difference of about 10 F is shown in Table II.

Table I. Summarized Data

Evaporator	Overall Coefficient (Btu/sq ft/F/hr)
Single-Tube	
Bare tube; falling film on external surface	450-700
Dropwise condensation on coated external surface of tube; falling film on internal surface	1000-4000
37-Tube	
Coated external surfaces of tubes; falling film on internal surfaces	400-650

Table II. Comparison Data

Circulation	Overall Coefficient (Btu/sq ft/F/hr)
Natural[1]	300-400
Forced[2]	600-1200

DISCUSSION

The values for the coefficients for falling films on the internal surface and dropwise condensation on the coated external surface were 2.5 to 5.7 times the overall coefficients obtained from the runs when the falling film was on the external surface of the tube.

Dropwise condensation was observed over the entire surface coated with the polytetrafluoroethylene polymer when the heating steam was condensing on it. The action of condensation did not wash away the coating.

The data in Figure 10 shows a drop in heat-transfer coefficient with increasing levels of flooding in the 37-tube evaporator. This reflects the loss of surface area available for a thin film. The difference is not great and indicates that little advantage was being gained because of the apparent difficulty of maintaining a falling film on longer tube surfaces. It is suggested that very thin, wiped films are more advantageous and result in greater overall heat-transfer coefficients.

CONCLUSIONS

Dropwise condensation on a surface coated with a polytetrafluoroethylene polymer improves heat-transfer coefficients sufficiently to make this method a possibility for future design criteria. The coating was very effective in inducing dropwise condensation.

There is an advantage in water-film evaporation, but the difficulty of maintaining a falling film on long, vertical tubes suggests that some other method of obtaining thin films should be investigated.

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2. Hyatt, D. L., and J. A. Eibling. Methods of Improving Heat Transfer in Evaporators of Small Thermocompression Sea-Water Stills. Paper presented at the ASME-AICHE Heat-Transfer Symposium at Northwestern University, 18-21 August 1958.

3. Keenan, J. H., and F. G. Keyes. Thermodynamic Properties of Steam. John Wiley and Sons, New York, 1936.

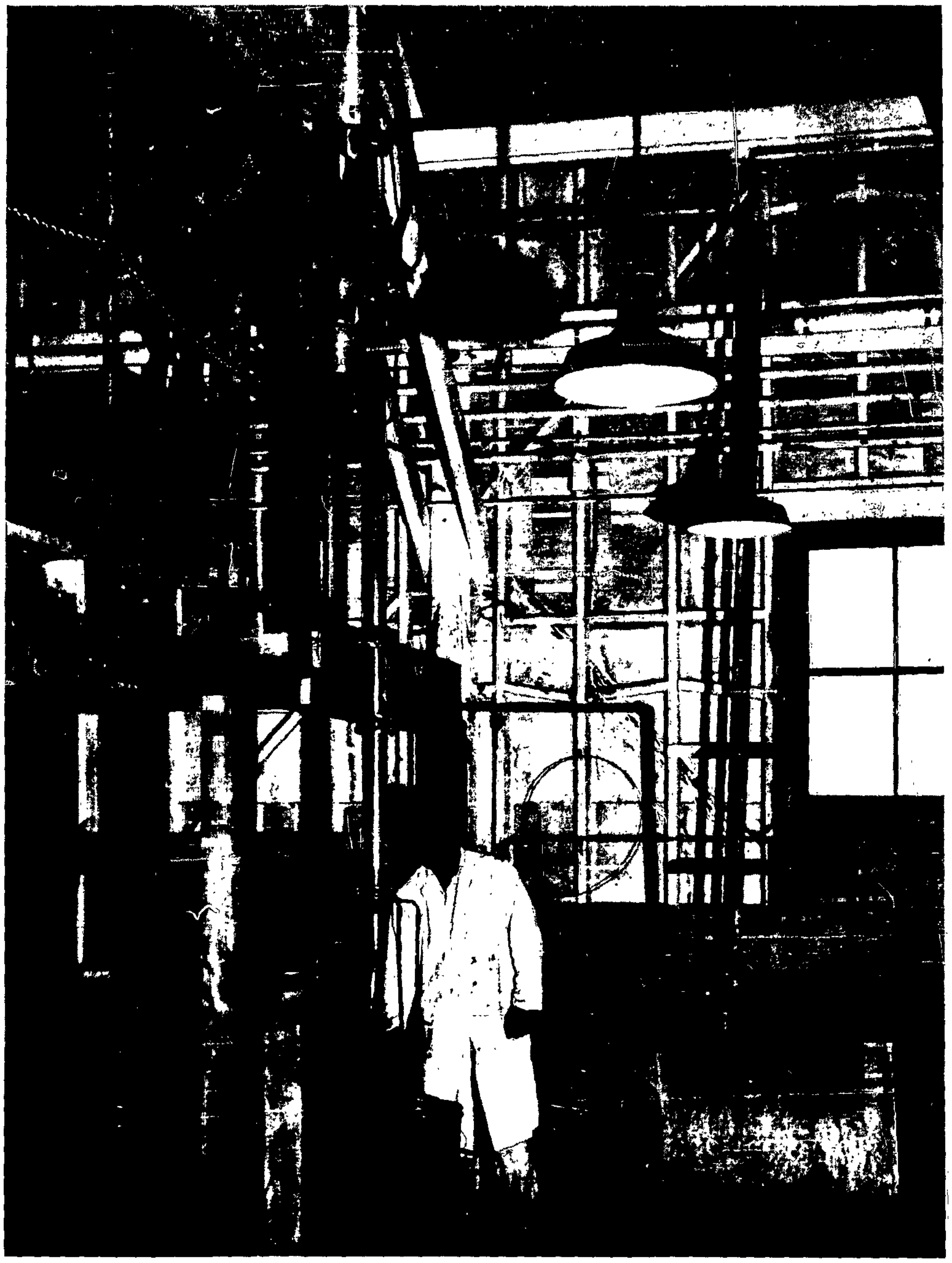

Figure 1. The single-tube evaporator, at its maximum length, with film falling on external surface.

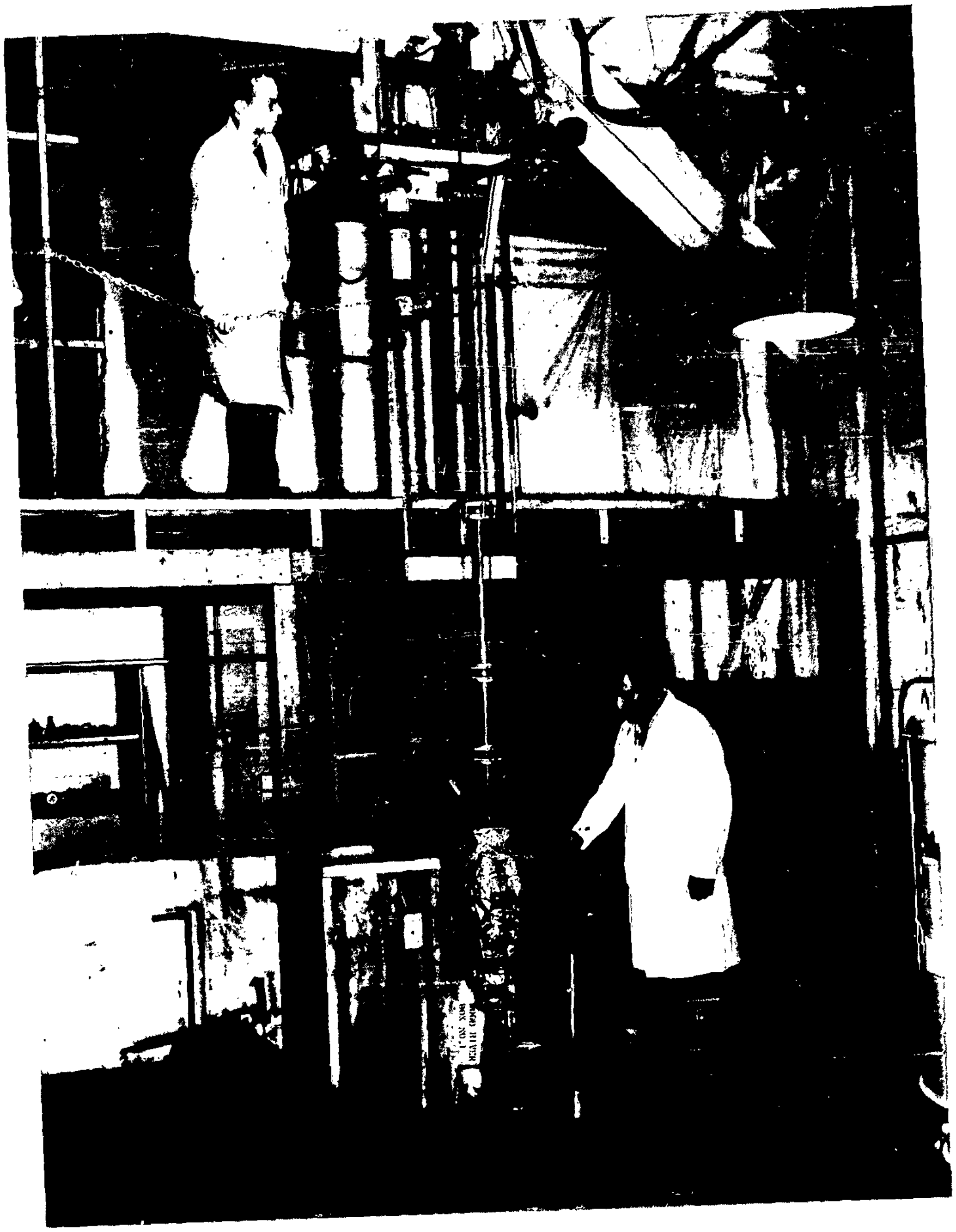

Figure 2. The single-tube evaporator, at its maximum length, with film falling on internal surface.

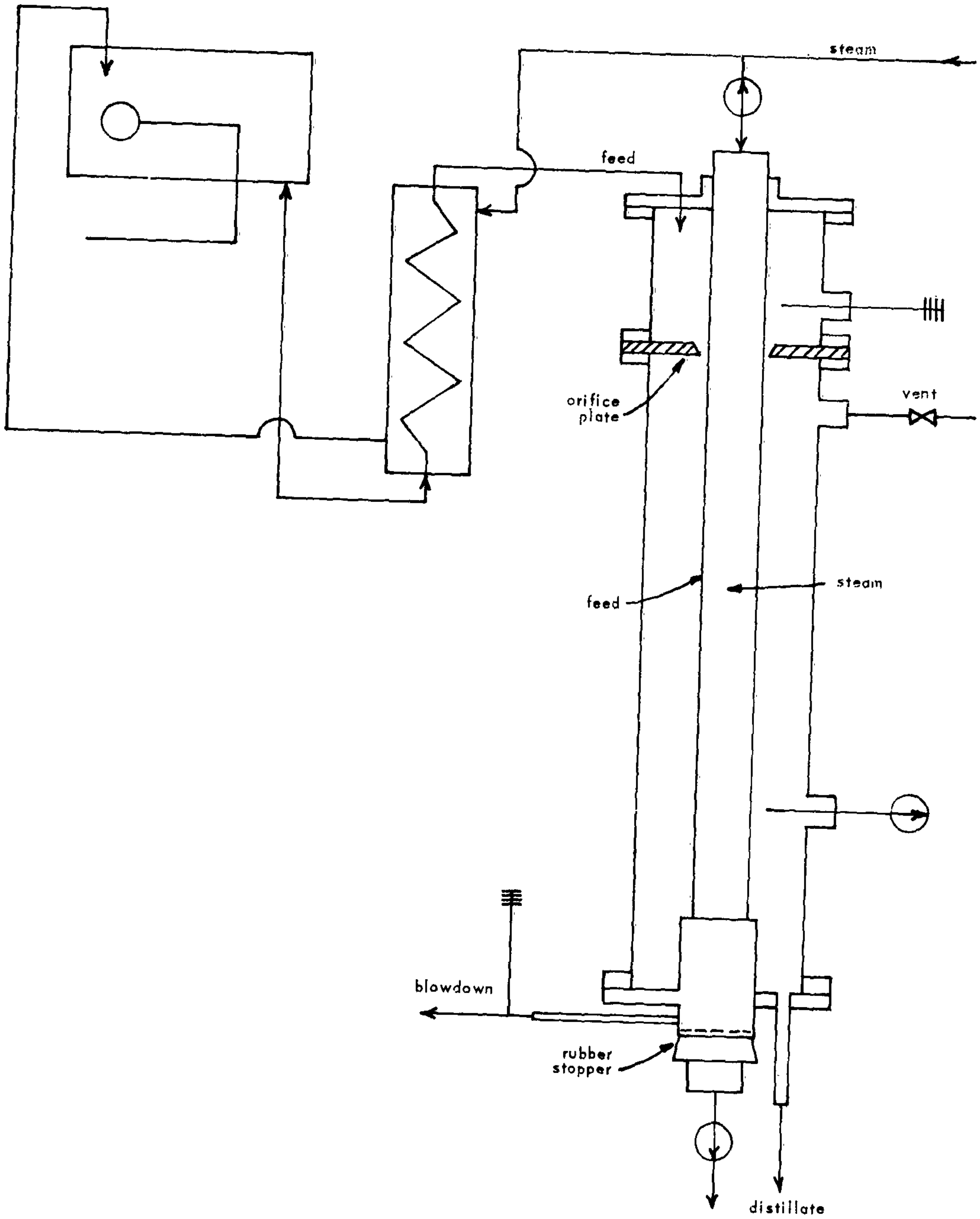

Figure 3. Flow diagram for falling film on external surface; condensation on internal surface.

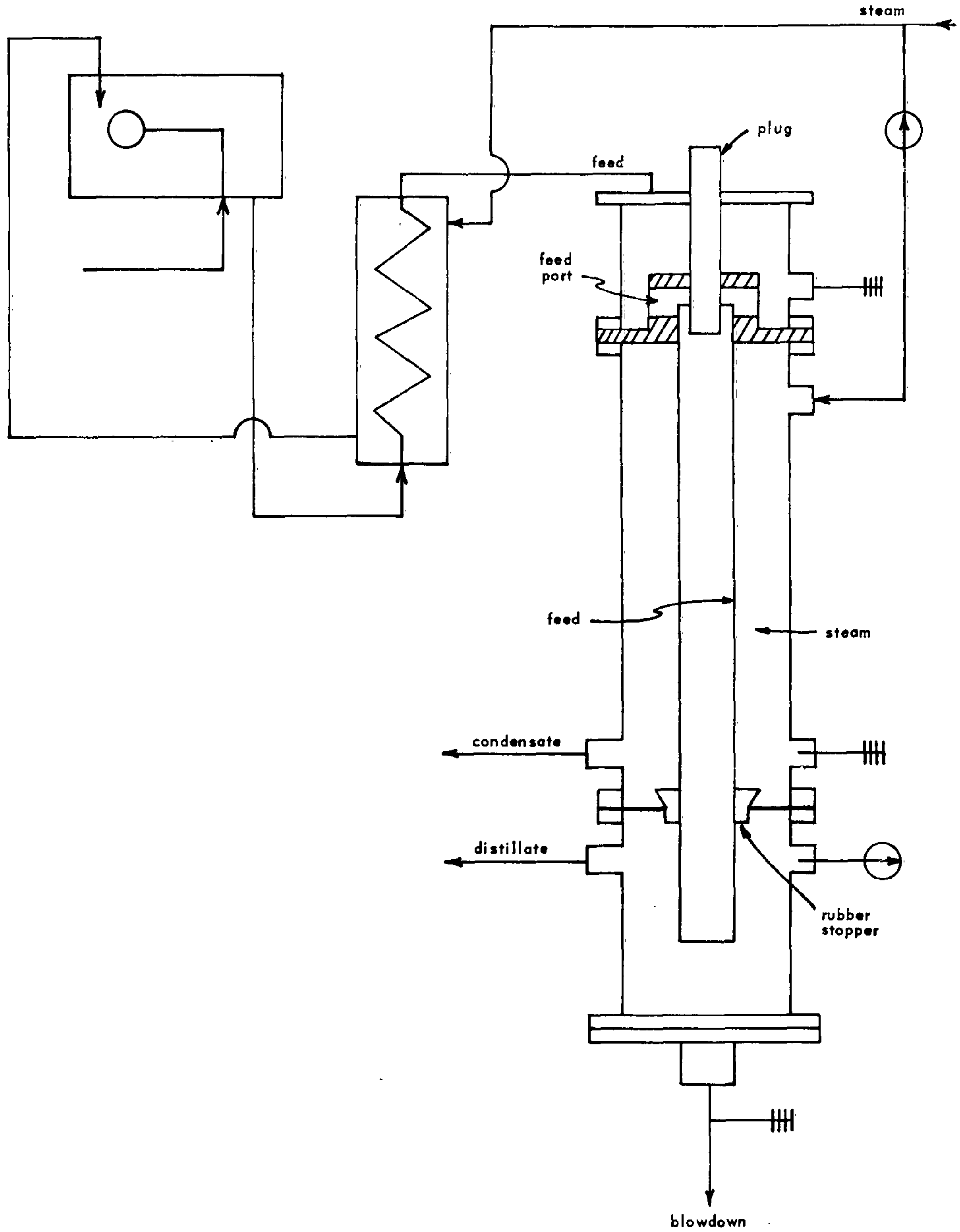

Figure 4. Flow diagram for falling film on internal surface; dropwise condensation on external surface.

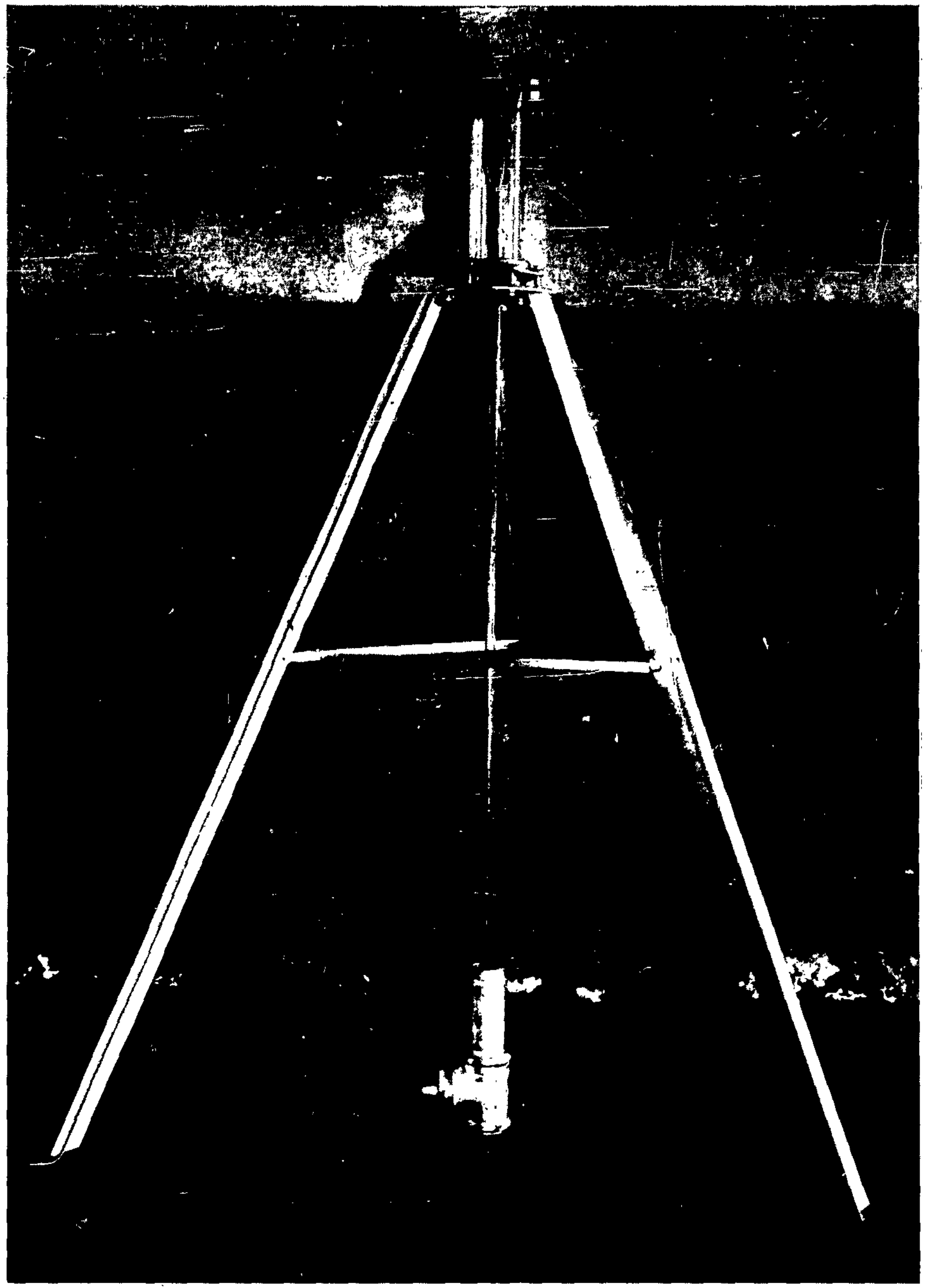

Figure 5. Apparatus for controlling thickness of film falling on external surface of tube.

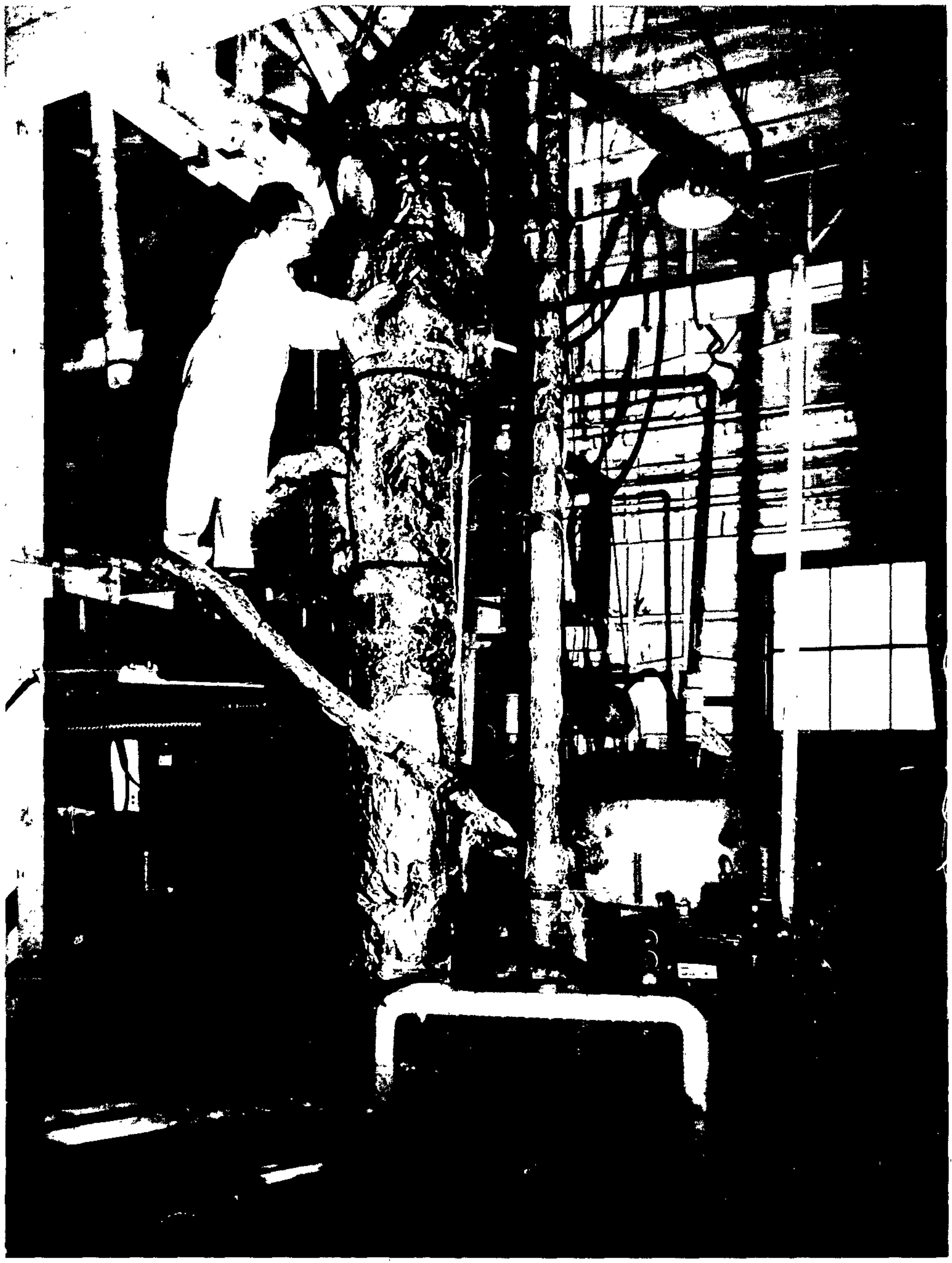

Figure 6. The 37-tube evaporator, diesel engine, and compressor.

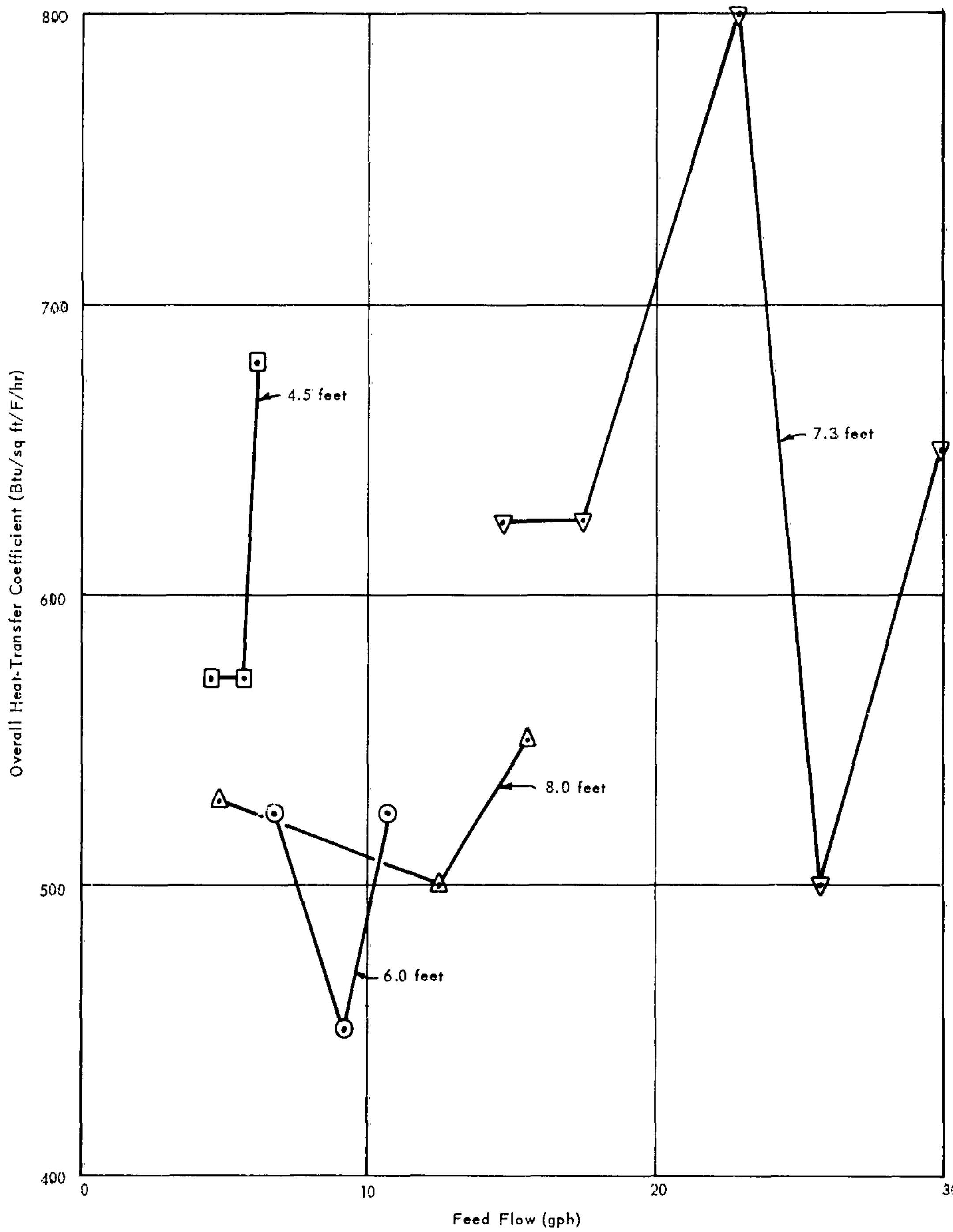

Figure 7. Results of first test series with bare tube and falling film on external surface of tube, showing effect of feed flow and tube length on overall heat-transfer coefficient.

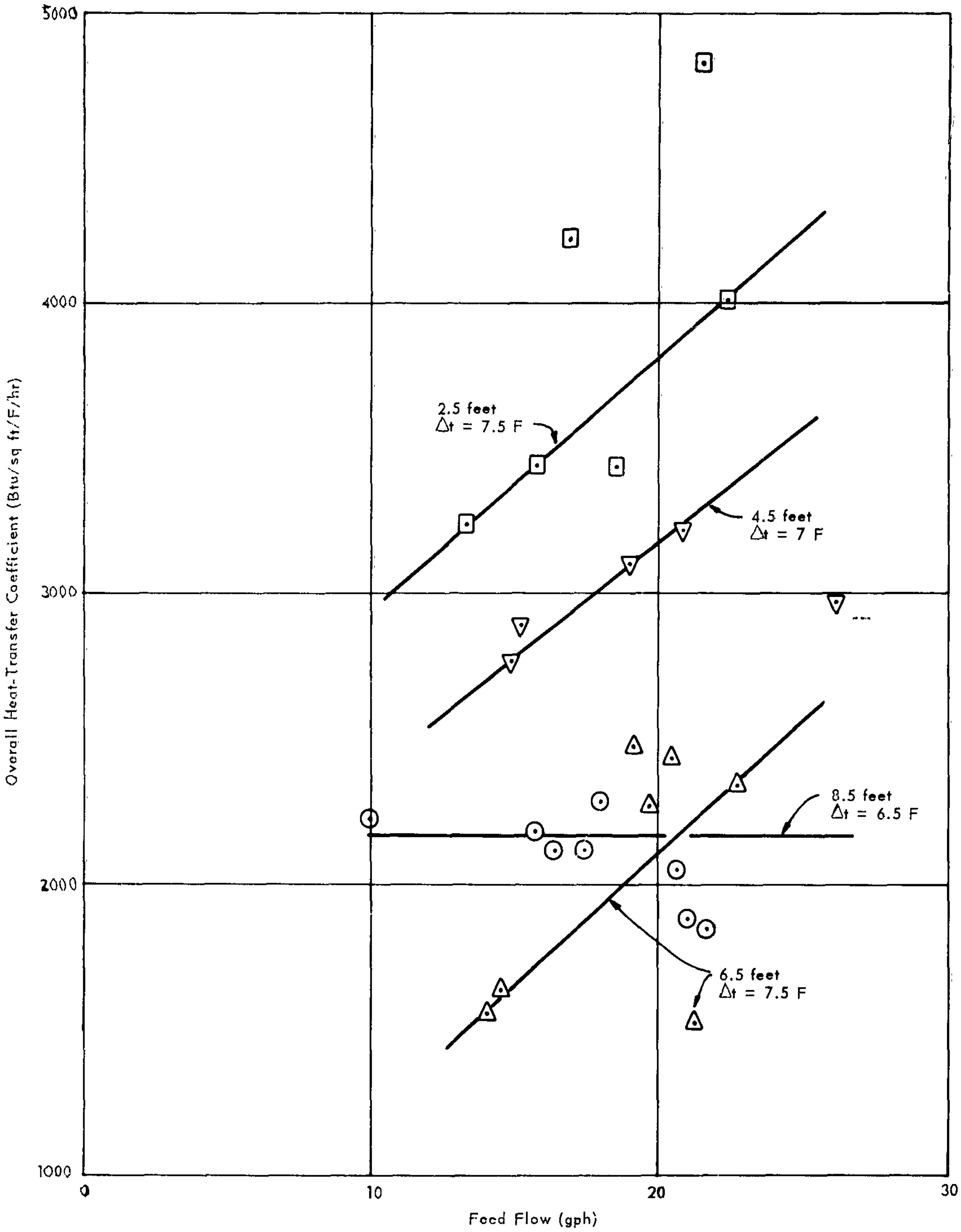

Figure 8. Results of tests on dropwise condensation on polytetrafluoroethylene-polymer-coated external surface, showing the effect of feed flow and tube length on the overall heat-transfer coefficient.

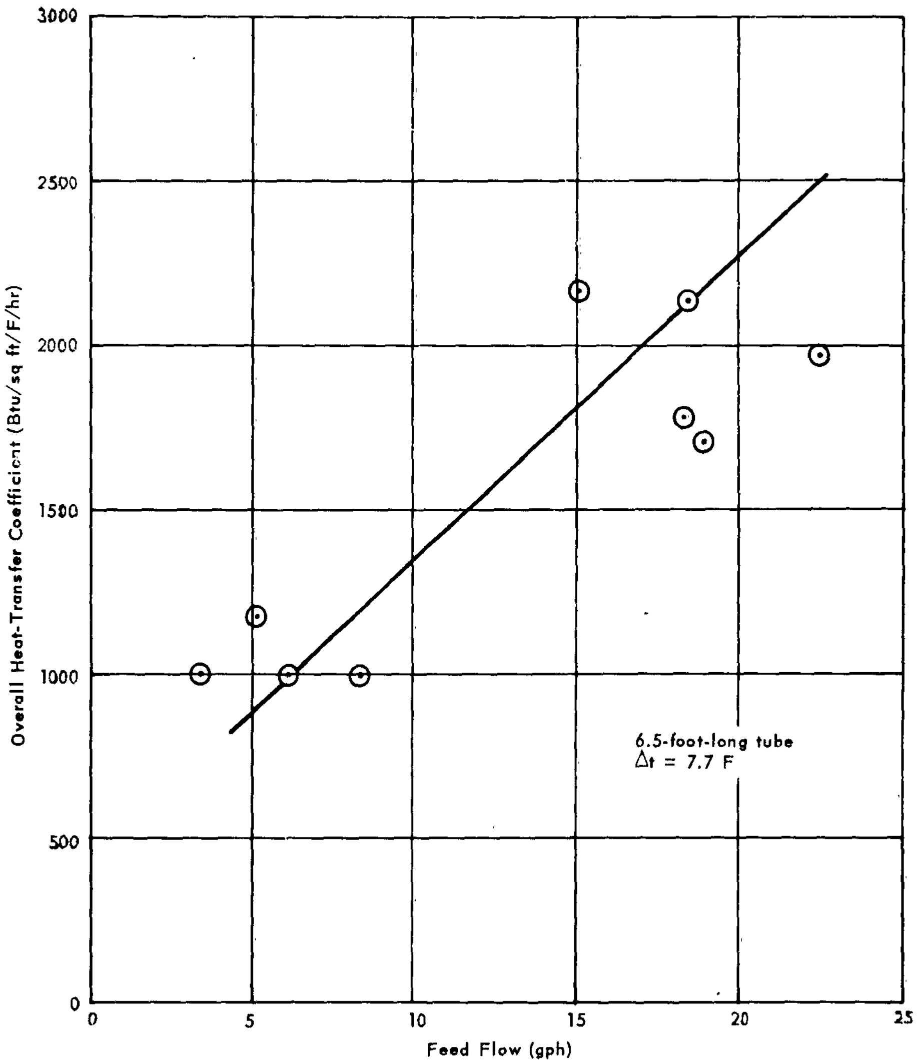

Figure 9. Results of tests on condensation on bare tube, showing the effect of feed flow on overall heat-transfer coefficient.

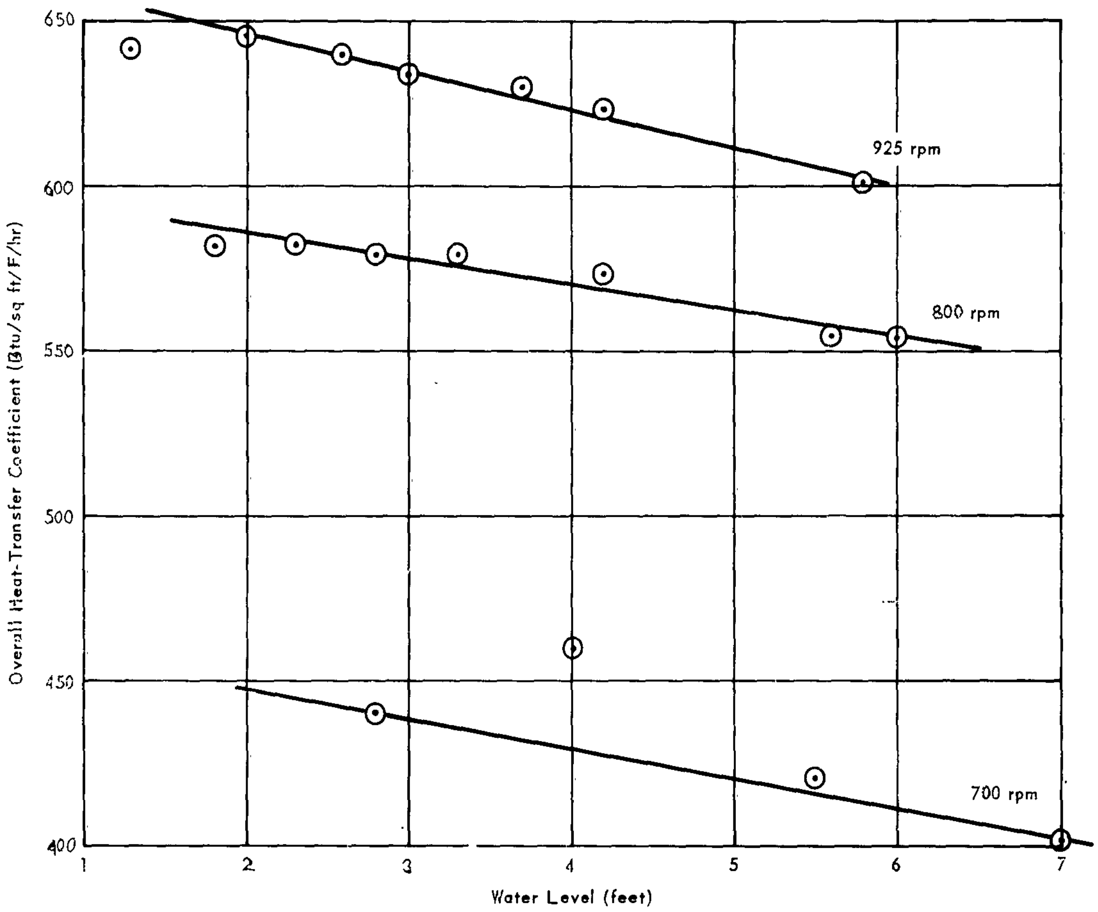

Figure 10. Results of dropwise condensation on 37-tube evaporator, showing effect of partially filled tubes and three different compressor speeds on the overall heat-transfer coefficient.

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